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THRESHOLDS FOR THE PERCEPTION OF ANGULAR ACCELERATION AS INDICATED BY THE OCULOGYRAL ILLUSION

Earl F. Miller, et al

Naval Aerospace Medical Research Laboratory
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13. ABSTRACT

The semicircular canal threshold, as measured by the perception of the oculogyral illusion, was determined by a double staircase procedure among 300 normal and 4 labyrinthine-defective subjects. A motorized chair with precise servo controls rotated the subject in a CW or CCW direction at rates varying in accordance with one of 24 extended trapezoidal-shaped profiles: 20 sec of constant acceleration, 25 sec at constant (terminal) velocity, 20 sec of constant deceleration and 25 sec at zero velocity. Accelerations ranged in logarithmic progression from 0.02 to 6.00°/sec^2. The illusion appeared as rightward or leftward movement of the visual target in the direction of acceleration. The target, a narrow collimated line of light, was contained within a goggle device worn by the subject and therefore fixed in relative position to him.

The method provided a brief and reliable (ρ = .70) threshold measurement. The majority of normal subjects revealed no substantial directional preponderance (CW vs CCW threshold). Threshold frequency distributions for the two directions of acceleration were similar and ranged in rate (deg/sec^2) from 0.20 to 0.950 with means of 0.146 (CW) and 0.152 (CCW), a median of 0.096 (CW, CCW), and modes of 0.096 (CW) and 0.076 (CCW). The threshold of response (deg/sec^2) in more than half the normal subjects was less than 0.10, in over three fourths was less than 0.20, in over 90 per cent less than 0.30, and 100 per cent less than 1.00. None of the labyrinthine-defective subjects perceived the illusion at the highest acceleration (6.00°/sec^2) employed.

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SUMMARY PAGE

THE PROBLEM

To measure thresholds for perception of angular acceleration as indicated by the oculogyral illusion in 300 normal subjects and in 4 subjects with bilateral labyrinthine defects.

FINDINGS

A motorized chair with precise servo controls provided clockwise or counterclockwise rotation of the subject about his vertical axis at rates that varied in accordance with one of 24 extended trapezoidal-shaped profiles. Each profile consisted of four phases: 20 sec of constant positive acceleration, 25 sec at constant (terminal) velocity, 20 sec of constant negative acceleration, and 25 sec at zero velocity. Acceleration ranged in logarithmic progression from 0.02 to 6.00°/sec^2. The threshold response to clockwise and counterclockwise acceleration was determined by a double-staircase method and was defined as the lowest of the 24 accelerations at which the subject could perceive the oculogyral illusion in three out of four or four out of six trials ($\geq$ 67 per cent). This illusion was perceived as an apparent rightward or leftward movement of the visual target in the direction of acceleration. The target was a narrow collimated line of light contained within a goggle device and therefore fixed in relation to the subject.

The method provided a brief and reliable (ρ = .70) means of measuring the thresholds. The great majority of the subjects revealed no substantial directional preponderance (CW vs CCW threshold). Threshold frequency distributions for the two directions of rotation were similar and ranged in rate (deg/sec^2) from 0.020 to 0.950 with means of 0.146 (CW) and 0.152 (CCW). The threshold of response (deg/sec^2) in more than half the normal subjects was less than 0.10, in over three-fourths was less than 0.20, in over 90 per cent was less than 0.30, and in 100 per cent was less than 1.00. None of the labyrinthine-defective subjects perceived the illusion at the highest acceleration (6.00°/sec^2) employed.

INTRODUCTION

The oculogyral illusion may be perceived by a person passively exposed to angular acceleration as apparent motion (in the direction of turn) of visual objects that are fixed relative to him (8). The illusion has its genesis in the semicircular canals and a knowledge of cupuloendolymph mechanisms, the role of adaptation effects and the influence of secondary etiological factors are all essential for predicting its behavior under different stimulus conditions (1, 2, 6, 9). Studies have shown that its perception under ideal test conditions yields lower threshold values than other canal response indicators: the manifestation of nystagmus, and the sensation and aftersensation of rotation (1, 3, 5, 7, 16). Indeed the thresholds of the illusion are so low that their measurement is limited by the precision of the rotating device. A highly sophisticated servo-controlled device, the Rotating Litter Chair (RLC), was developed expressly for determining with this indicator any changes in cupular thresholds of response that might occur during the prolonged weightless Skylab missions (14). The purpose of this report is to evaluate the RLC and a relatively short method for determining the thresholds of perception of the illusion in a large sample of normal subjects and in four deaf persons with severe bilateral labyrinthine defects.

PROCEDURE

SUBJECTS

Three hundred normal healthy men, ranging in age from 17 to 49 years, served as test subjects; most (261) of these subjects were less than 26 years of age. This group was comprised of 203 pilots or pilot trainees, 44 enlisted personnel, and 53 civilians. Each had demonstrated normal otolith and semicircular canal function, as indicated, respectively, by ocular counterrolling (11, 12) and caloric response (10). In addition, four deaf individuals with severe bilateral labyrinthine defects, as defined in Table I, served in determining non-labyrinthine influences upon the perception of rotation.

APPARATUS

Rotating Litter Chair

The rotating litter chair (RLC) (Figure 1) is a relatively lightweight (~ 145 lb) motor-driven rotational chair device that is described elsewhere in detail (14). A servo-controlled d-c brush-type motor is programmed to rotate automatically a seated subject at any one of 24 velocity versus constant time (90 sec) profiles (Figure 2) within extremely narrow limits of precision (Table II). The 24 extended trapezoidal-shaped profiles yielded in progressive logarithmic steps a range of constant accelerations from $0.02^{\circ}/sec^2$ (step 1) to $3.00^{\circ}/sec^2$ (step 23); two log units of acceleration separated steps 23 and 24. The man-supporting superstructure and motor of the RLC are directly coupled to eliminate gear slack and perceptible vibration and therefore meet the physiological requirement of eliminating small performance errors that are normally within the sensitivity range of the delicate vestibular organs.

Table I

Clinical Findings in Four Deaf Subjects with Bilateral Labyrinthine Defects

Subj.	Age	Deafness: Etiology	Deafness: Age of Onset (yrs)	Hearing: R	Hearing: L	Caloric Response*: R	Caloric Response*: L	Date of Clinical Tests	Counterrolling Index†
GR	48	Mastoiditis	12	Nil	160 dB	Negl.	Negl.	1967	60
GU	22	Meningitis	$4\frac{1}{2}$	$\geq$ 145 dB	$\geq$ 145 dB	Negl.	Negl.	1967	89
MY	26	Meningitis	8	None	None	None	None	1967	99
PE	33	Meningitis	12	None	None	Negl.	Negl.	1967	77

*Negligible or no observable nystagmus when tympanum irrigated with water at a temperature of 11° C or less.
†Calculated as one-half the sum of the eye roll measured in minutes of arc at the 50° rightward and leftward tilt positions.

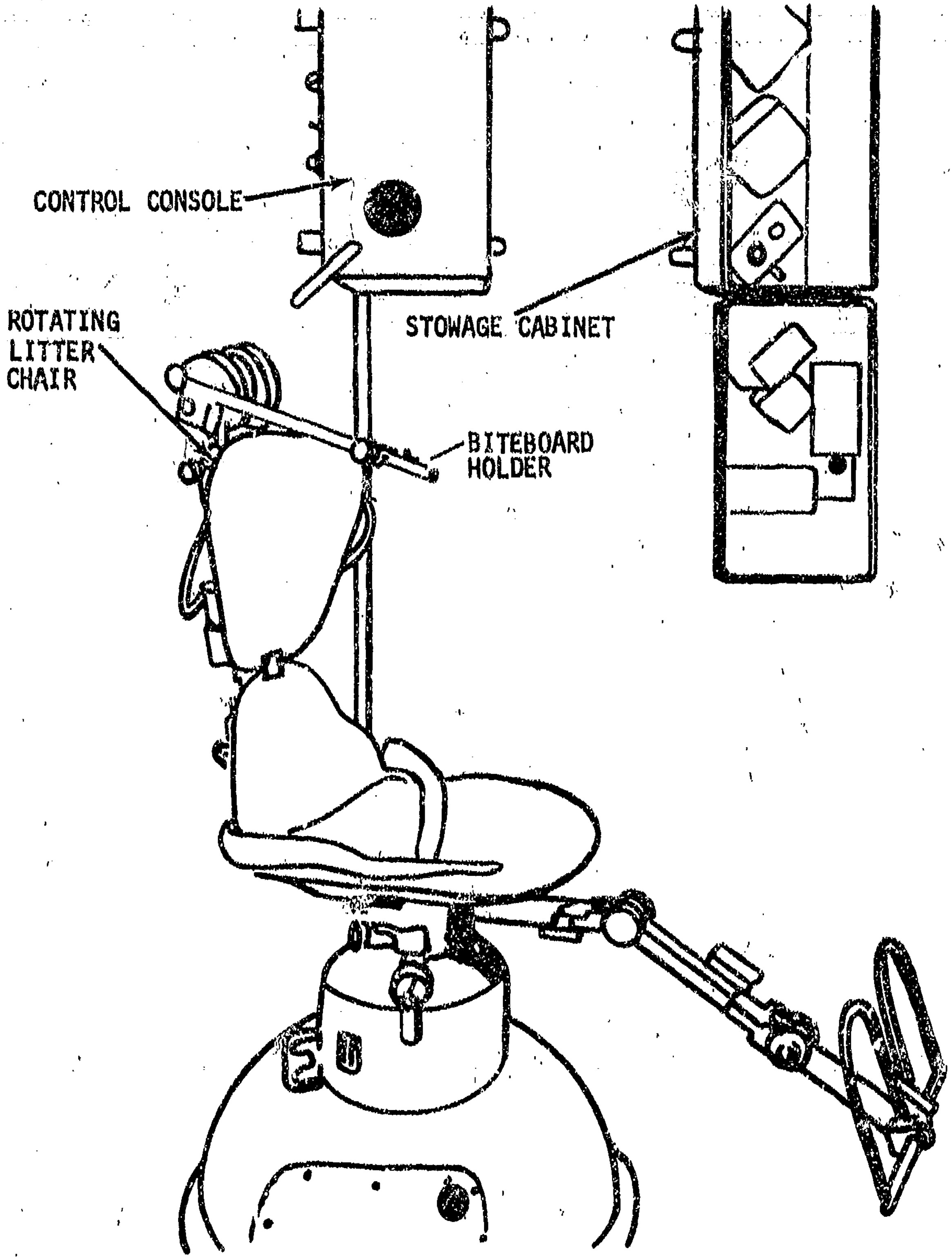

Figure 1

Diagram of the Rotating Litter Chair and Ancillary Equipment, Including the Control Console and Stowage Cabinet for the Vestibular Test Goggle and Biteboards

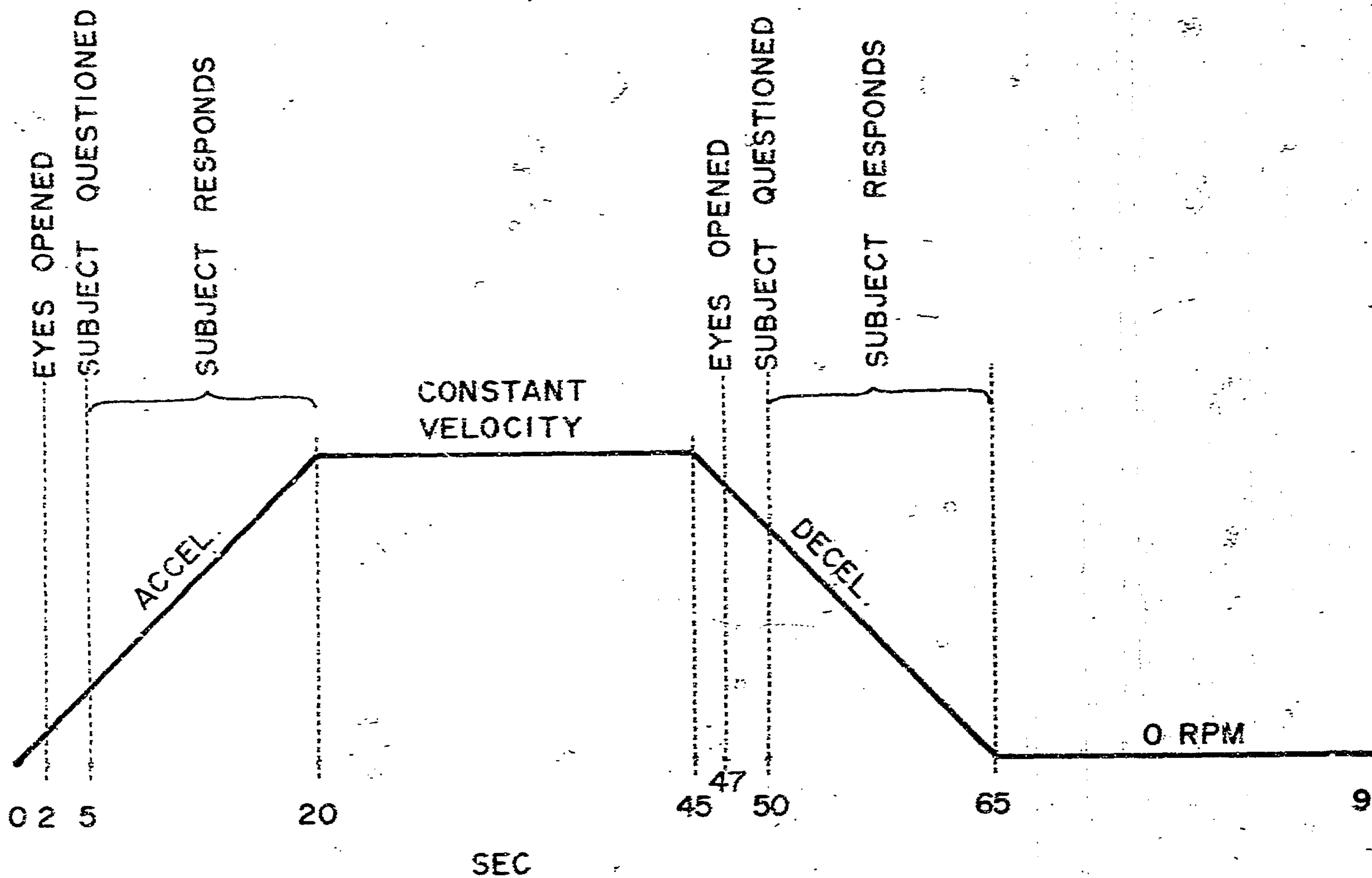

Figure 2

Diagram of a Test-Cycle Profile Indicating Chair Rotational Mode and Experimental Activity as a Function of Time

Table II

Rotating Litter Chair (Oculogyral Illusion Test Mode) Performance Values

Log Step	Angular Acceleration ($^\circ/sec^2$)	Precision ($^\circ/sec^2$)	Peak Velocity (rpm)
1	0.020	± 0.0007	0.067
2	0.024	± 0.0004	0.080
3	0.030	± 0.0004	0.100
4	0.038	± 0.0004	0.127
5	0.048	± 0.0008	0.160
6	0.060	± 0.0004	0.200
7	0.076	± 0.0004	0.253
8	0.096	± 0.0005	0.320
9	0.120	± 0.0004	0.400
10	0.150	± 0.0004	0.500
11	0.190	± 0.0005	0.633
12	0.238	± 0.0006	0.793
13	0.300	± 0.0007	1.000
14	0.380	± 0.0012	1.267
15	0.475	± 0.0005	1.583
16	0.600	± 0.0008	2.000
17	0.760	± 0.0018	2.533
18	0.950	± 0.0018	3.167
19	1.200	± 0.0024	4.000
20	1.500	± 0.0018	5.000
21	1.900	± 0.0036	6.333
22	2.400	± 0.0030	8.000
23	3.000	± 0.0028	10.000
24	6.000	± 0.0084	20.000

Vestibular Test Goggle

The vestibular test goggle (VTG), described in detail elsewhere (13), is a self-contained device worn over the subject's eyes (Figure 3). The collimated line-of-light target, the only thing visible to the subject, is self-illuminated by a radioactive source (tritium gas, 100 millicuries, AEC license Number 09-06979-03) contained in the goggle. Two knurled knobs permit the target to be rotated 360° about its center and moved vertically, from a straight-ahead position, ± 20° about the center of rotation of the viewing right eye; the left eye is occluded by being covered with a portion of the goggle. The device is held on the face by its attachment to a biteboard assembly which, in turn, is secured by an adjustable support connected to the RLC (Figure 4). The distance between the ocular and occlusal planes is adjusted so that the subject's visual axis in its primary position is essentially in the "horizontal" plane containing the optic axis of the target system. The target was found to be completely visible to all subjects having a wide range of interpupillary distances; so, no means of lateral adjustment was incorporated in the goggle.

METHOD

The subject's fitness for testing was determined by a questionnaire (Appendix A). The oculogyral illusion was demonstrated at the time of the biteboard fitting by having the subject observe the apparent movement of the test-goggle target during gentle side-to-side head movements.

The subject was then secured in a seated position within the RLC, and his biteboard and the VTG were affixed to the support mechanism of the chair. He engaged the biteboard with his teeth and donned the VTG by tilting his head forward 20°. The target viewed by his right eye was adjusted so that it appeared vertical and straight ahead. The purpose of the fixed head tilt was to place the "plane" of the lateral canals closer to the plane of rotation.

A sound source for signalling the normal subject was situated directly over his head, which eliminated it as a cue to the chair's rotational direction; the labyrinthine-defective subject was signalled by lightly tapping the top of his head. The rotational chair was located in a test cubicle, which permitted this area to be darkened and thereby removed any possible influence of any small openings between the goggle's padding and the face. During testing, auditory directional cues were effectively removed by having the normal subject wear earphones. All subjects used hand-held, color-coded lights to signal, when requested, the direction of apparent movement of the target. After one of the 24 acceleration rates was selected on the basis of the predetermined test schedule and subject performance, the program start switch of the RLC was pressed. After 2 seconds of constant positive acceleration, the subject was signalled to open his eyes; after 5 seconds' accumulative time, he was signalled again to judge whether the target appeared to move rightward or leftward, or to remain stationary. If the subject did not respond after 15 seconds' accumulative time, a third signal was given. If no response was received within 20 seconds' accumulative

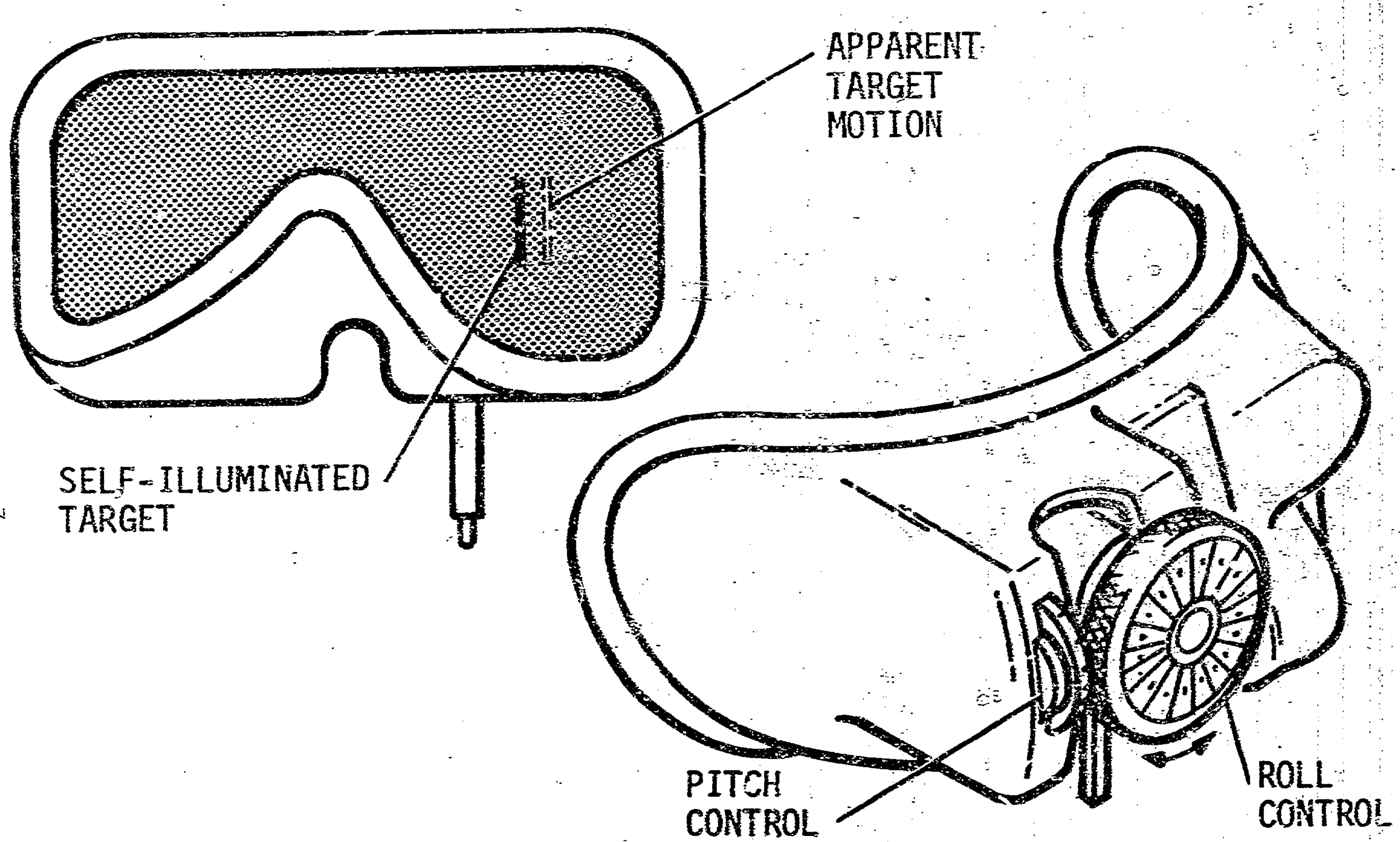

Figure 3

Diagram of the Vestibular Test Goggle (VTG). At Top a Rear View of the Goggle Illustrates an Apparent Rightward Movement of the Line-of-Light Target as Viewed by the Right Eye. The Bottom Half-Front View Shows the Knurled Knobs for Adjusting the Roll and Pitch Positions of the Target.

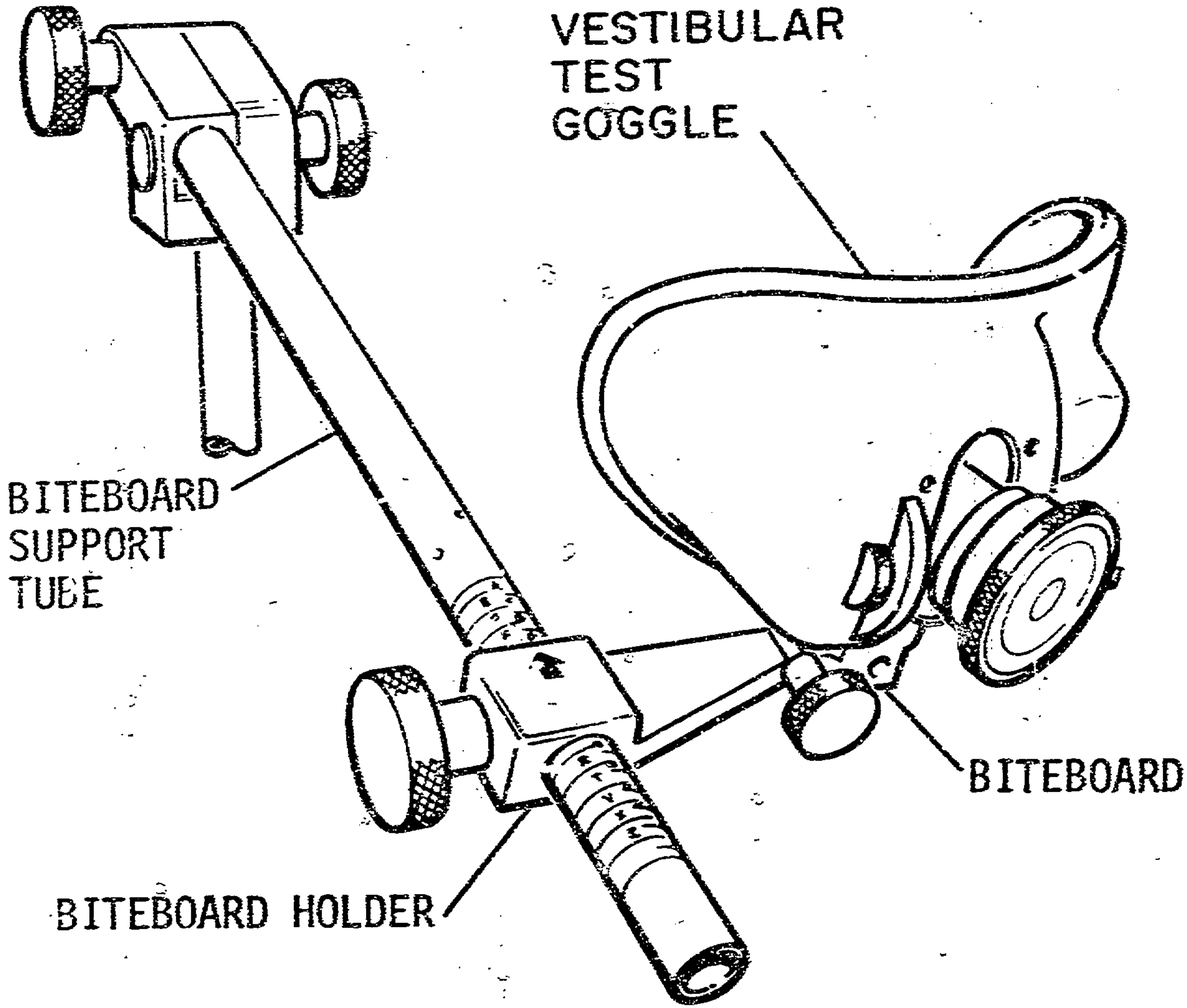

Figure 4

Diagram of the Biteboard Support System Connecting the Test Goggle and Biteboard to the RLC time, the end of the constant acceleration period and the beginning of the 25-second constant velocity phase, it was assumed and recorded that no movement was perceived. The subject was instructed to close his eyes immediately after each response.

The down ramp of the profile required the subject, as in positive acceleration, to open his eyes at 2 seconds and to respond between the 5th and 20th second after deceleration had begun. After reaching zero rpm, the RLC remained stationary for at least 25 seconds. In some cases the next profile was not initiated for up to several minutes when: 1) the total test time exceeded 30 minutes, 2) when the subject requested additional test time, or 3) for operational reasons, e.g., wiping the goggle lens to remove a moisture film that occasionally was found to accumulate. The direction of rotation among the profiles was varied at random according to a predetermined schedule.

Our early experimental probes had indicated that a brief period of feedback training at an acceleration level well above response threshold was necessary to establish that the subject understood the task and could readily observe the illusory movement. The subject was also fully apprised that apparent movement of the target in this situation did not also require its apparent displacement, particularly at or near his response threshold level. During training conducted at acceleration step 12, or higher if necessary, the subject was informed of his results and coached until he could consistently identify the direction of the oculogyral illusion. During the actual test, the subject was not provided this feedback.

Mechanically, the stimulus to the cupuloendolymph system and therefore its response with clockwise (CW) acceleration are equivalent to those for counterclockwise (CCW) deceleration, as in the reverse sense are the pair of complementary directions of acceleration and deceleration. For convenience, each stimulus pair is henceforth identified only by its associated direction of acceleration.

A response threshold for each of the two directions of acceleration was defined as the lowest acceleration at which the subject could correctly identify the expected direction of apparent movement in three out of four, or four out of six trials. When a difference in perception of the illusion for the two directions of acceleration was manifested at any step, the threshold for the direction of better performance was pursued first. If, for example, at least one response associated with the first test profile (usually step 12) was correct, testing proceeded to step 6. For those subjects meeting or exceeding the threshold criterion at step 6, further testing followed a double-staircase method (4) that was limited to the range of accelerations between; if the criterion was not met at step 6, the test ranged from step 6 to the initial test step. If both responses at the initial test step were incorrect, the two staircases proceeded between usually step 15 and the initial acceleration step until a response threshold for CW as well as CCW acceleration was established. The test was completed in more than half the subjects within 30 minutes, and in most within 40 minutes, although occasionally about 1 hour was required. In no case was the subject tested longer than 30 minutes without one or more rest periods prior to completion of the test; each rest period of about

5 minutes was instituted with the subject remaining in the RLC but with his head removed from the goggle and biteboard support.

The oculogyral illusion threshold of each normal subject was measured by this procedure on two different occasions, separated by at least 24 hours, in order to determine test-retest reliability.

RESULTS AND DISCUSSION

The large number of trials and long test periods often covering many days or weeks that are typical in measurements of a response threshold were avoided in this study without apparent undue compromise in sensitivity or reliability by using 24 logarithmic step levels of accelerative stimuli. On a linear basis this schedule introduces ever-increasing increments of acceleration among the progressive test steps with the result, desirable from a practical point of view, that differentiability among individuals decreases as an indirect function of threshold level.

Directional preponderance, i.e., a difference in threshold for CW and CCW acceleration, was not manifested in 35 per cent, was less than 0.1°/sec^2 in 84 per cent, and less than 0.2°/sec^2 in 94 per cent of the normal subjects; the remaining subjects revealed a preponderance that ranged from 0.2 to 0.7°/sec^2. Furthermore, a moderately high correlation (ρ = .72) was found to exist between data obtained with CW and CCW acceleration. A substantial directional (CW vs CCW) preponderance in the OGI threshold response would therefore not be the expected result in a normal individual. A follow-up investigation of the small number of subjects who demonstrated relatively large directional preponderances was not conducted, but a study of unilaterally labyrinthectomized individuals gave some evidence that an acute unilateral vestibular disturbance may cause a preponderance (15).

The individual thresholds for CW and CCW acceleration were averaged to obtain a single measure of test-retest reliability which proved also to be moderately high (ρ = .70). This level of reliability and the brief test period required make the method feasible as a clinical-type test of semicircular canal function. The large sample of normative data offers a substantial basis for comparing the OGI thresholds of response of individuals with possible vestibular disfunction.

Frequency distributions of the oculogyral illusion threshold values among all the normal subjects for CW and CCW acceleration are presented in Figure 5. The distributions were similar for the two directions of angular acceleration and ranged in terms of rate (degrees per second per second) from 0.020 to 0.950, with means of 0.146 (CW) and 0.152 (CCW), a median of 0.096 (CW, CCW), and modes of 0.096 (CW) and 0.076 (CCW). These same distributions expressed in terms of cumulative frequency are given in Figure 6. The distributions on a linear scale are skewed right: More than half the individual thresholds fell below 0.10°/sec^2; over three-fourths were less than 0.20°/sec^2; over 90 per cent less than 0.30°/sec^2; and 100 per cent less than 1.00°/sec^2. These findings compare well with those of Clark and Stewart (2) who found that the OGI thresholds of their 32 subjects ranged from 0.04°/sec^2 (close to the lower limit of their

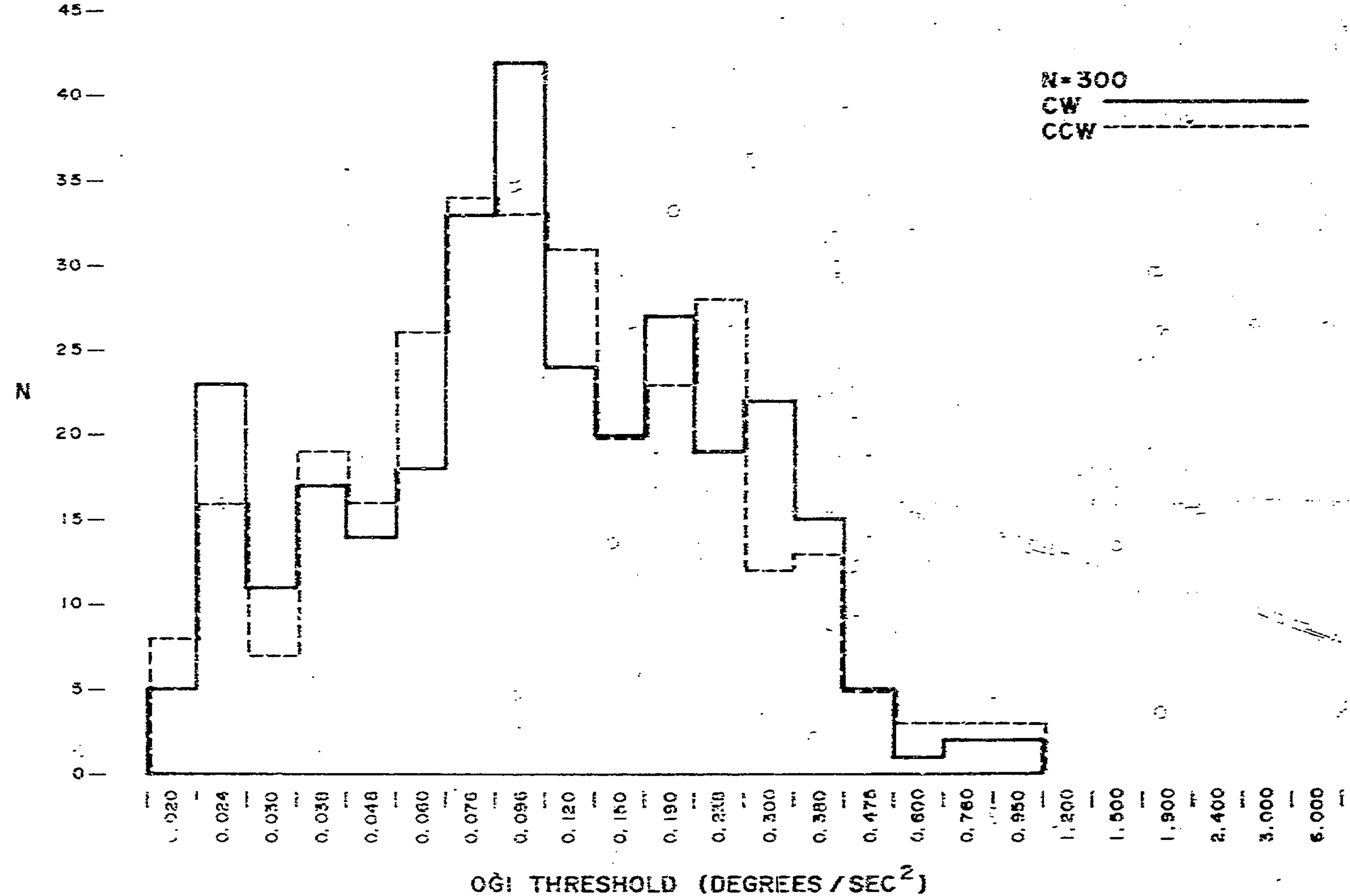

Figure 5

Frequency Distribution of the Oculogyral Illusion Threshold for Clockwise (CW) and Counterclockwise (CCW) Directions of Acceleration Among 300 Normal Subjects

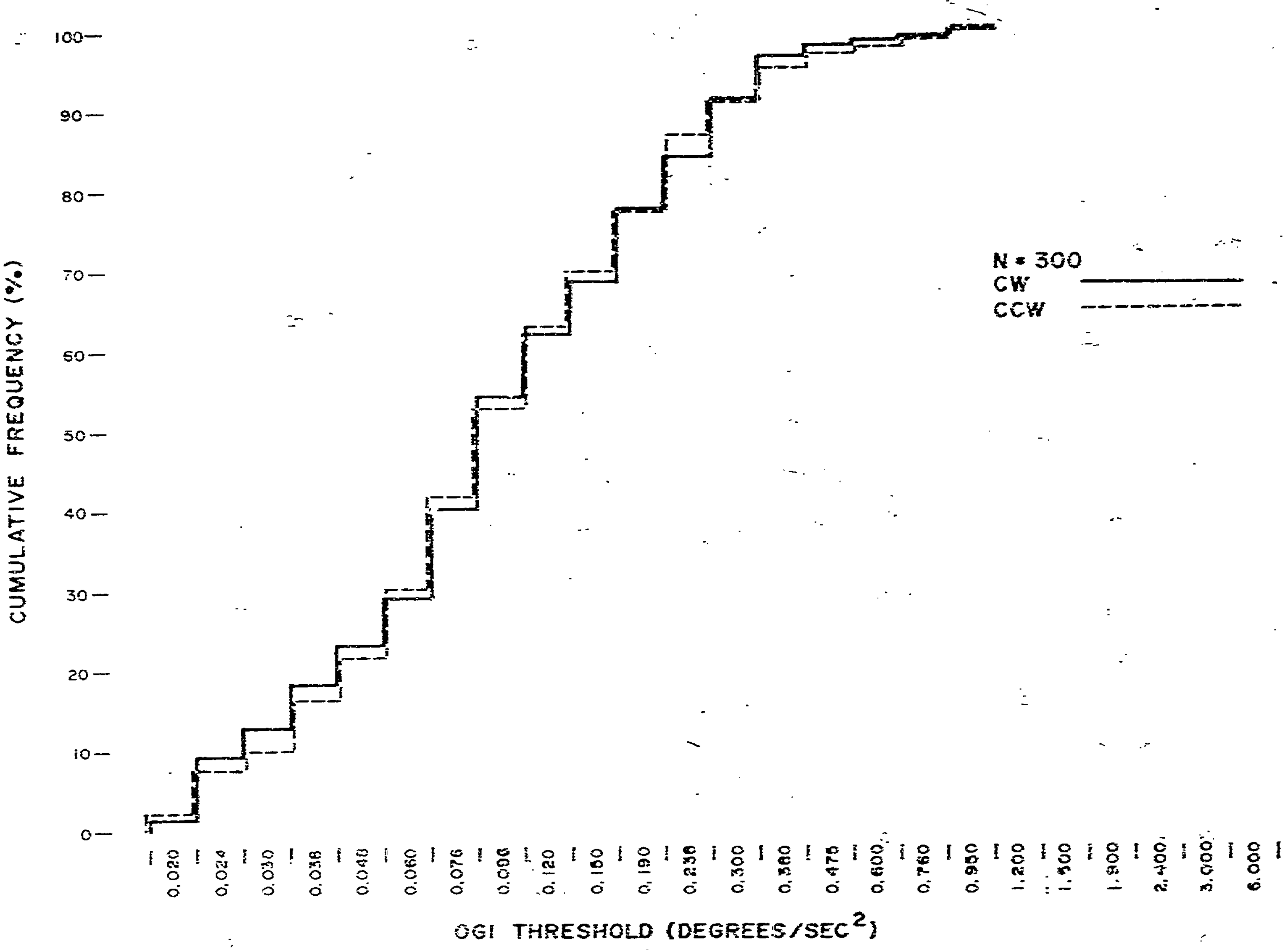

Figure 6

Cumulative Frequency Distributions of the Average Threshold for Clockwise (CW) and Counterclockwise (CCW) Directions of Acceleration Among 300 Normal Subjects device) up to $0.28^{\circ}/sec^2$, and confirm their conclusion that normal healthy adult men have semicircular canals that are highly sensitive to accelerative stimulation.

All labyrinthine-defective subjects failed repeatedly to perceive the oculogyral illusion at the highest acceleration step ($6.00^{\circ}/sec^2$) offered by the RLC test device, giving further evidence that the basic underlying mechanism for this illusion is the cupuloendolymph system.

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APPENDIX A

Subject's Pre-experimentation Questionnaire

Name/Number	Date	Time
Last First Middle Initial		

Have you been well throughout the past week?
YES NO

Are you free of all major health complications? (e.g., heart disease, diabetes, back trouble, etc.)
YES NO

Are you in your usual state of fitness today?
YES NO

If no to one or more of the above questions, specify problem and include severity, time course, where localized, etc.

How much alcohol have you consumed during the past 24 hours? (No. and kinds of drinks)

How much tobacco in past 3 hours?
Cigarette(s) Cigar(s) Pipe(s) full

Have you taken drugs or medicine of any kind in past 24 hours?
YES NO

If yes, were they?
- Analgesic (aspirin)
- Sedative or tranquilizer
- Antimotion sickness remedy (anti-histamine)
- Other, including eye and ear drop medications

If name of drug(s) is known, please list below:

How many hours sleep did you get last night?

Was this sufficient?
YES NO

How anxious are you regarding your participation in these tests?
NOT MINIMAL MODERATE GREAT VERY GREAT

How many hours since your last meal?

How many cups of fluid have you had in the past 2 hours?

Have you served as a subject in any rotational test within the past 48 hours?
YES NO

If yes, endpoint reached.